Renewable and Sustainable Energy Reviews 16 (2012) 6183–6190

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Determination of the optimum hybrid renewable power generating systems for Kavakli campus of Kirklareli University, Turkey

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ARTICLE INFO

Article history:
Received 8 February 2012
Received in revised form
2 July 2012
Accepted 15 July 2012
Available online 30 August 2012

Keywords:
PV array
Hybrid power systems
Fuel cell
Renewable energy
Optimization

ABSTRACT

This study is to search for possibilities of supplying the load demand of Kavakli campus of Kirklareli University with solar energy and the fuel cell power generating system (electrolyzer/hydrogen tank/fuel cell) by using the HOMER software due to the fact that hybrid power systems with renewables can significantly reduce emissions which are caused by utilization of non-renewable power sources. In this study, various hybrid systems will be examined and compared among themselves considering cost of energy (COE), renewable fraction, total net present cost (NPC) and hydrogen production. Additionally, this study will seek whether a fuel cell can be integrated into the hybrid systems. According to the study results, the grid connected systems appear cost-effective as expected. Although the grid-connected photovoltaic (PV) hybrid system has the lowest COE and NPC, the grid-connected PV/fuel cell hybrid system with COE, 0.294$/kWh has a slightly higher cost than the optimum one. It is strongly believed that this system may be chosen because it is a cleaner system and its emissions are fairly low.

Contents

1. Introduction

Energy is a fundamental constituent of economical growth and socio-economical development. Energy needs of countries

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http://dx.doi.org/10.1016/j.rser.2012.07.017

increase with the rising population. Turkey, having population more than 70 million, has 1.31% increase each year in population which is foreseen to reach 83.4 million in 2022 [1]. Furthermore, Turkey has many rich energy sources, especially renewable energy sources such as geothermal, wind, hydraulic, wave, biomass and solar energy. However, it cannot utilize them very efficiently. Solar energy is one of the most popular renewable energy sources and is non-depletable, site-dependent, non-polluting, and potential source of alternative energy as well [2,3]. However, it has an unstable and variable characteristic. Due to intermittent nature of the solar energy, only solar power cannot meet the continuous energy demand. Therefore, solar power is used together with hybrid systems which are combined with one or more of the renewable energy resources like solar and wind energy. Generally, there are many studies about the hybrid wind/photovoltaic (PV) system, PV/diesel or wind/diesel. Most of them deal with cost and economic optimization, system design and optimization in hybrid energy systems [4]. Some of them are shortly described as following. Dufo-Lopez and Bernal-Austin optimized a PV–diesel system using two different ways. One of the ways is applied to a PV–diesel system using the HOGA software program. The other way includes a classical design method which is based on the available energy under worst-case conditions [5]. Similarly, Muselli et al. developed a methodology for calculating the correct size of a PV-hybrid system and for optimizing its management [6]. Moreover, Ashari and Nayar presented dispatch strategies for the operation of a solar PV–diesel–battery hybrid power system using "set points". They determined the optimum values of set points for starting and stopping of the diesel generator to minimize the overall system costs [7]. Similarly, Nfah et al. modeled solar–diesel–battery hybrid power systems for the electrification of typical rural households and schools [8]. Additionally, apart from the studies on renewable energy systems excluding fuel cell and electrolyzer components, there are also many studies on the PV hybrid system combined with fuel cell power generating unit as well. One of them was carried out by Perez [9] and Lehman et al. [10]. Since then, several systems have been developed and evaluated in recent years [11,12]. For Zoulias et al. [13] the use of FCs in stand-alone power systems may prove to be a large market niche. Thus, FCs may compete, in the mid-term, with currently available commercial technologies, such as diesel generators and battery banks. Hollmuller and Joubert studied the performance of a privately owned PV–hydrogen production and storage installation in a one-family house at Zollbruck i.e. in Switzerland [11]. Moreover, Ghosh et al. [12] introduced the PHOEBUS demonstration plant that supplied energy to part of the Central Library in Forschungszentrum Julich, Germany. Furthermore, Hwang et al. developed a mathematical model for a stand-alone renewable power system, referred as the "PV–fuel cell (PVFC) hybrid system", which maximizes the use of a renewable energy source [14]. Finally, Mohd presented a renewable energy/hydrogen based power system model to provide electricity to a coastal residential area in east coast area (Kuala Terengganu) of Malaysia [15].

This study is to search for the possibilities of supplying the load demand of Kavakli campus of Kirklareli University which is currently supplied by the electricity grid, with the solar energy and hydrogen fuel cell power generating system (electrolyzer/hydrogen tank/fuel cell) since renewable energy based hybrid power systems can significantly reduce the amount of emission gases from the non-renewable power system (conventional power systems). In this study, the National Renewable Energy Laboratory's (NREL) optimization tool "HOMER" will be used in identifying probable hybrid configurations and their applicability among various hybrid systems, considering some parameters, COE, renewable penetration rate, NPC, and hydrogen production.

2. Description of Kavakli campus of Kirklareli University

2.1. Location and population of the campus

Kavakli campus of Kirklareli University is located in the Northern Marmara region. Its coordinates are 41,650 latitude and 27,166 longitudes. Area of the campus is 50,000 m^2. Besides, since it is a newly formed university and it was established in 2007, it contains only two institutions, six faculties, seven research and development centers and its student population is about 6000 [16].

2.2. Load profiles of the campus

Energy requirement of the campus is currently supplied by electricity grid. Load data used in this study was obtained from TEIAS. According to the load data, the average daily energy demand of the campus is about 485 kWh [17].

HOMER simulates the operation of a system by making energy balance calculations for each hour in a year [18]. The hourly load profiles are not available for a whole year, so HOMER is used to synthesize the load profiles (with randomness) by entering the values for a typical day. Either day-to-day randomness or time-step-to-time-step randomness is taken as 5% in the study. According to the load data, the minimum load demand occurs between 00:00 and 06:00 . Load profile of the Kavakli campus is shown in Fig. 1.

In summer, load demand is higher because air conditioning systems in offices are used more. For summer, maximum value of the load demand is 36 kWh which occurs between 10:00 and 11:00.

2.3. Solar energy potential of the campus

Solar radiation data of the region where Kavakli campus is located was obtained from Turkish State Meteorological Service (TSMS) in the year 2010 [19]. Monthly average solar energy density values are shown in Fig. 2. Annual average solar energy density value is calculated as 4.864 $\mathrm{kWh\,m^{-2}\,d^{-1}}$. HOMER synthesizes solar radiation values for each hour of a year by using the Graham algorithm. This algorithm produces realistic hourly data, and it is easy to use because it requires only the latitudes and the monthly averages [18].

3. Three major parameters in the economic analysis

3.1. Calculation of the annual real interest rate for Turkey

The annual real interest rate is one of the HOMER's inputs. The annual real interest rate is related to the nominal interest rate

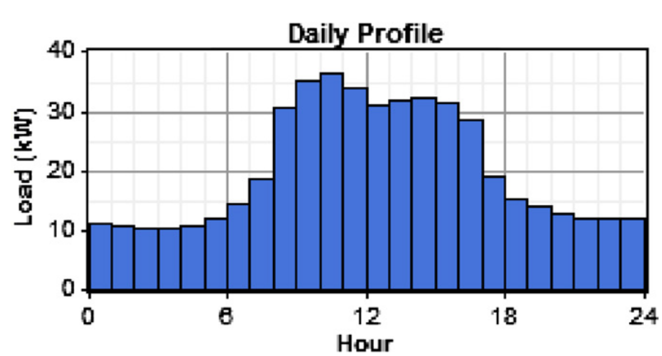

Fig. 1. Load profile of Kavakli Campus of Kirklareli University.

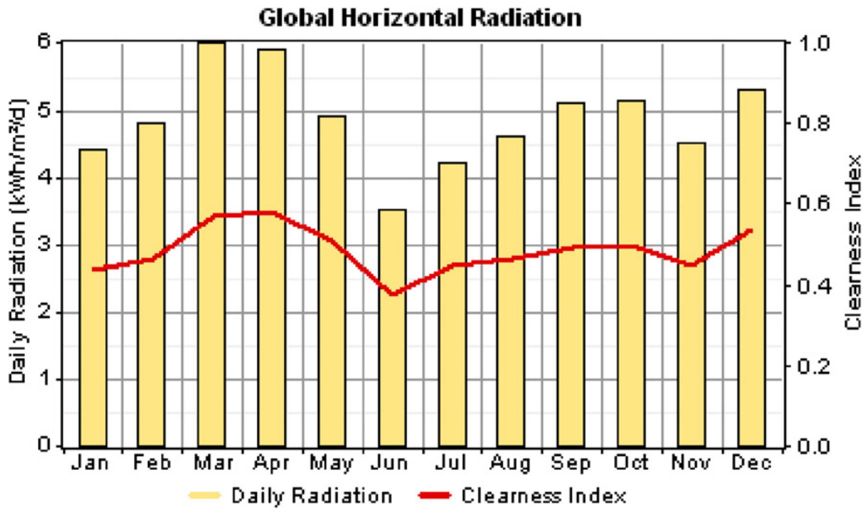

Fig. 2. Monthly average solar energy density values of Kırklareli, Turkey.

by the following equation:

$$i = \frac{i_0 - f}{1+f} \tag{1}$$

where i is the real interest rate, i_0 is the nominal interest rate (the rate at which you could get a loan), and f is the annual inflation rate.

For Turkey, i_0=9% (interest rate was taken from the Turkish Central Bank in August 13, 2011) and f=6.4% (annual inflation rate was taken from the Turkish Central Bank at the end of 2010) are used. With these values, using Eq. (2), real interest rate is found to be 2.45% as calculated below [20,21]:

$$i = \frac{0.09 - 0.064}{1+0.064} = 0.0245 \tag{2}$$

In HOMER simulations, 2.45% is used for real interest rate.

3.2. Levelized cost of energy

HOMER defines the levelized COE as the average cost/kWh of useful electrical energy produced by the system. The equation for the COE is as follows:

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC} + E_{grid,sales}} \tag{3}$$

where $C_{ann,tot}$ is total annualized cost ($/yr), $E_{prim,AC}$ is AC primary load served (kWh yr^{-1}), $E_{prim,DC}$ is DC primary load served (kWh yr^{-1}), and $E_{grid,sales}$ is total grid sales (kWh yr^{-1}). The total annualized cost is the sum of the annualized costs of each system component, plus the other annualized cost. It is an important value because HOMER uses it to calculate both the levelized COE and total NPC [21,22].

3.3. Net present cost (NPC)

The present value of the cost of installing and operating the system over lifetime of the project is also referred as lifecycle cost. Project lifetime in this study is considered as 20 yr. The total NPC is HOMER's main economic output. All systems are ranked according to NPC, and all other economic outputs are calculated for the purpose of finding the NPC. The NPC is calculated according to Eq. (4) [21,22]:

$$C_{NPC} = \frac{C_{ann,tot}}{\mathrm{CRF}(i, R_{proj})} \tag{4}$$

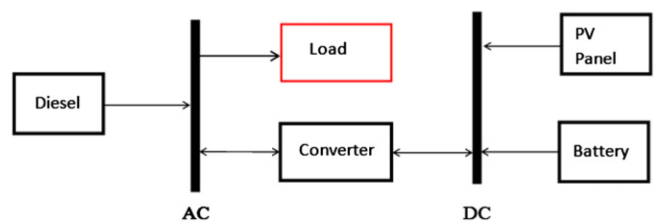

Fig. 3. All components of PV–diesel hybrid power generating systems.

where $C_{ann,tot}$ is the total annualized cost ($/yr), CRF is the capital recovery factor, i is the real interest rate (%), and R_{proj} is the project lifetime (yr). The capital recovery factor is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is

$$\mathrm{CRF}(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5}$$

where i is real interest rate (%) and N is number of years.

4. Hybrid power generating system components

Various stand-alone and grid connected hybrid systems discussed for Kavakli campus mainly comprise PV panels, fuel cell, hydrogen tank, electrolyzer, battery, converter, diesel generator and grid. Main components in each system discussed in this study are shortly summarized below.

4.1. PV–diesel power generating system

The schematic diagram of PV–diesel power system components are presented in Fig. 3.

The hybrid power generating system consists of a diesel generator, PV arrays, batteries and power converters. Some inputs for each component of the hybrid system such as cost, number of units, capacity, operating hours and other specifications are needed to run the simulation using the HOMER software. The details of the system components were obtained from manufacturers of the equipments and previous studies [23–26]. The descriptions of these components are given below.

Diesel generator: The cost of a commercially available diesel generator may vary from $250 to $500 kW^{-1} [23]. For larger units per kW cost is lower and for smaller units cost is more. A 50 kW

diesel generator is used in this power system as the peak power demand is less than 50 kW. Regarding the study carried by Dalton, capital, replacement and operational costs are taken as \$450, \$400 and \$0.150 h^{-1}, respectively. Meanwhile, the lifetime is 15,000 h. In this study no diesel generator (0 kW) or a 50 kW unit was used for simulation by HOMER.

PV-array: The installation cost of PV arrays may vary from \$6.00–\$10.00 W^{-1}. A 1 kW solar energy system installation and replacement costs are taken as \$7000 and \$6000, respectively [23]. Various sizes of PV array are considered, ranging from 0 to 150 kW in this study. The lifetime of the PV array is taken as 20 yr and there is no tracking system in the PV arrays.

Batteries: Batteries are supposed to have a big share in the total cost of small-scale stand-alone power systems. A Surrette-6CS25P model battery with 6 V, 1156 Ah and 9645 kWh is chosen in this simulation [24]. The estimated lifetime of the battery is 5 yr and the cost of one battery is \$1250 with a replacement cost of \$1100 while the operation and maintenance cost is \$0.02 yr^{-1}. Meanwhile, the number of units for the battery stacks is in the range of 0–200 units.

Power converter: A power electronic converter maintains flow of energy between the ac and dc components. For a 1 kW system the installation and replacement costs are taken as \$800 and \$750, respectively. Four different sizes of converters (0, 15, 30 and 45 kW) are considered for the simulation. Meanwhile, lifetime of the power converter is considered to be 15 yr with an efficiency of 90% [15,25].

4.2. The grid connected PV power generating system

The grid connected PV power system is powered by the grid and it does not include diesel generator unlike the stand-alone PV–diesel hybrid power system. All components of the hybrid system are the same as those in the standalone PV–diesel hybrid system mentioned in Section 4. All components of the hybrid system are indicated in Fig. 4.

4.3. The stand-alone PV–hydrogen power generating system

The conventional hybrid power system can be easily upgraded to the stand-alone PV–hydrogen hybrid power system that is schematically designed as in Fig. 5.

All the meteorological data used here is the same as the previous simulation. The equipments of this hybrid system are PV array, battery, fuel cell, hydrogen tank, electrolyzer, and power electronic converter. In this hybrid energy system, the type of battery has the same properties with one used in the previous system, which is Surrette 6CS25P. In order to determine optimum combination of equipment dimensions, different sizes of the battery are selected. Stand-alone PV–hydrogen system components are described more detail below.

PV-array: For this hybrid system, the PV capital, replacement, and operation and maintenance costs, as well as lifetime of the PV array are the same as those in Section 4.2. The considered sizes of the PV array are in the range of 0–200 kW.

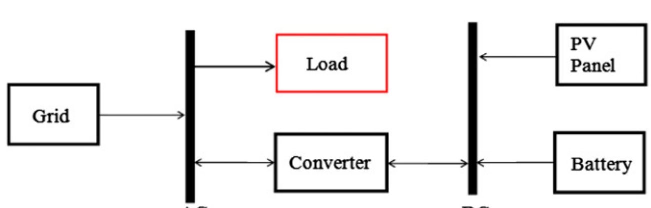

Fig. 4. Configuration of grid gonnected PV power generating systems.

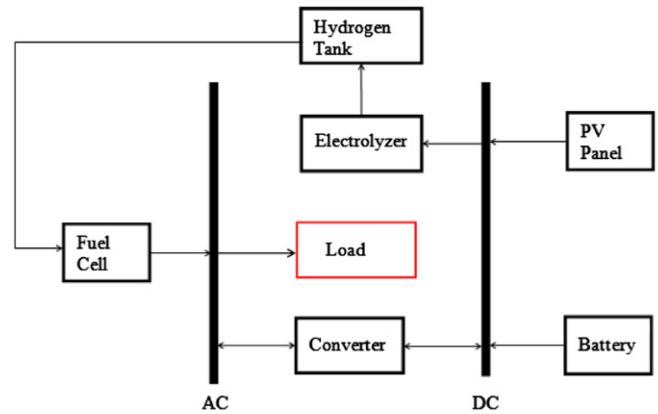

Fig. 5. Configuration of the stand-alone PV–hydrogen power generating system.

Electrolyzer: Currently, the production cost of electrolyzers is between \$1500 and \$3000 kW^{-1}. With improvements in polymer technology, control systems and power electronics it is expected that costs would reduce much in 10 yr [23]. In this analysis, various sizes of electrolyzer (0–50 kW) are considered. A 1 kW system has a capital cost of \$2000, a replacement cost of \$1500 and an operational and maintenance cost of \$20. Meanwhile, lifetime is considered as 25 yr with efficiency 75% [15].

Power converter: Power electronic converter in this hybrid system has similar properties with one in the previous system. For a 1 kW system, the installation and replacement costs are taken as \$800 and \$750, respectively. Three different sizes of the converter with power capacity between 10 and 60 kW are taken in the model.

Fuel cell system: The cost of fuel cell varies greatly depending on the type of technology, reformer, auxiliary equipments and power converters. At present, a fuel cell cost varies from \$3000 to \$6000 kW^{-1} [23]. Here, the capital, replacement and operational costs are taken as \$3000, \$2500 and \$0.020 h^{-1} for a 1 kW system, respectively. Four different sizes of fuel cells are taken in the simulation process: 0 (no fuel cell used), 5, 10 and 20 kW. Meanwhile, lifetime and efficiency of the fuel cell are taken as 40,000 h and 50%, respectively.

Hydrogen tank: Cost of a tank with 1 kg hydrogen capacity is assumed to be \$1300. The replacement and operational costs are taken as \$1200 and \$15 yr^{-1}, respectively. Five different sizes (0, 20, 40, 60 and 80 kg) are included to widen the search space for a cost effective configuration, and the lifetime is also considered as 25 yr.

4.4. The grid connected PV–hydrogen power generating system

In this grid connected hybrid system, the grid supplies no power to the electrolyzer device in order to produce hydrogen in the case of the deficiency of power supplied by the PV system. Only excess electricity, which was produced in PV panels but was no longer used in meeting the demand, serves to activate the electrolyzer. The schematic appearance of the hybrid system is indicated in Fig. 6. Such hybrid system includes the similar equipments as those in the stand-alone PV–hydrogen hybrid system described in Section 4.3.

Unlike the standalone PV–hydrogen hybrid system, it is a grid connected system. The single rate that refers to the fix power price, sellback rate and demand rate is set for the case of residential consumers. The fix power price is 0.1\$ kWh^{-1}

while the sellback rate and demand rate are 0.05$ kWh^{-1} and 0.00$ kWh^{-1} month^{-1}, respectively. The grid system has two working conditions. When the renewable energy system produces more power than the demand, the excess power is fed back into the grid. Otherwise, when the system does not produce enough power, then the required power can be provided from the grid [15].

5. Results and discussions

In this study, four stand-alone and grid connected hybrid systems are considered and analyzed using the HOMER software to determine the optimum hybrid systems for the campus in Kirklareli. The optimum (best) configurations obtained for these hybrid systems are presented in detail in Table 1.

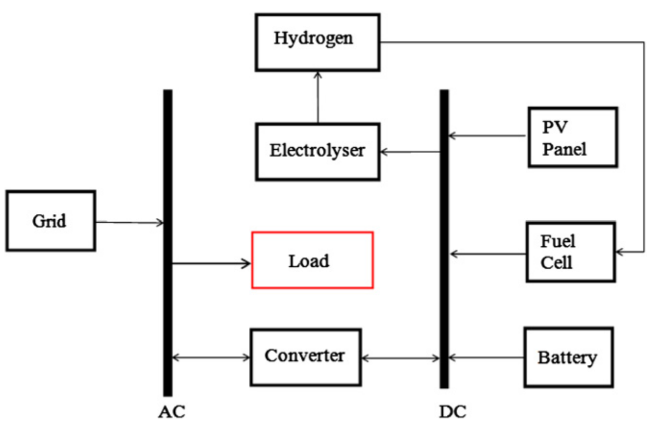

Fig. 6. Configuration of the grid connected PV–hydrogen power generating system.

Furthermore, all outputs about the economic and environmental parameters of these hybrid systems that was simulated by means of the HOMER software, are detailed in Table 2.

In this section, considerable outputs concerned with each optimum stand-alone and grid connected hybrid systems, which were obtained in the study employing the HOMER software, will be presented item by item in the following sub-sections.

5.1. The stand-alone PV–diesel hybrid system

- The HOMER software completed the simulation within only 9 s.
- The least COE of this system is \$0.817 kWh^{-1} and results from the combination of 120 kW PV, 50 kW diesel generator, 150 kW battery and 45 kW converter.
- The renewable energy fraction of this hybrid system is 0.736.
- Diesel fuel consumption in this hybrid system is only 21,025 lt.
- Simulation results show that the consumption of diesel fuel and amounts of emission gases (CO_2, NO_x, CO and SO_x) per year are reduced about 75% by the introduction of 120 kW PV panels into the system when compared with the stand-alone diesel system using only diesel generator as power supplier.
- The distribution of annualized cost for each component of the stand-alone hybrid PV energy system is presented in Table 3. The capital cost, total NPC and COE for this optimal hybrid system are \$1,068,000, \$1,849,654 and \$0.817 kWh^{-1}, respectively. The most expensive cost, \$954,020 comes from the PV panels. It is followed by diesel generator, battery and converter costs.

Table 1
Optimum configurations for the considered hybrid systems.

PV (kW)	Gen (kW)	FC (kW)	Battery	Converter (kW)	Electrolyzer (kW)	H_2 tank (kg)	Grid (kW)	Initial capital (\$)	Operating cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. frac.	FC (h)
120	50	–	150	45	–	–	–	1,068,000	61,146	1,849,654	0.817	0.74	–
40	–	–	–	25	–	–	1000	300,000	29,075	838,768	0.256	0.31	–
190	–	5	800	40	5	40	–	2,439,000	54,362	3,446,346	1.051	1.00	24
50	–	10	–	30	10	20	100	450,000	27,759	964,381	0.294	0.38	16

Table 2
All outputs associated with some economical and environmental parameters of all the systems considered in the study.

Systems considered in the study	COE (\$/kWh)	Total cost (\$)	Renewable fraction	Capital cost (\$)	Fuel		Emissions (kg yr^{-1})					
					Diesel (lt yr^{-1})	H_2 production (kg yr^{-1})	CO_2	CO	Unburned hydrocarbons	Particulate matter	SO_2	NO_x
Diesel	1.023	2,315,640	0	4500	82,719	–	217,826	538	59.6	40.05	437	4798
Standalone PV/diesel	0.817	1,849,654	0.74	1,068,000	21,025	–	55,365	137	151	10.3	111	1219
Standalone PV/fuel cell	1.051	3,446,346	1	2,439,000	–	75.6	0	0.257	0	0	0	2.3
Grid connected PV	0.256	711,060	0.31	82,000	–	–	103,815	0	0	0	450	220
Grid connected PV/fuel cell	0.294	964,381	0.38	450,000	–	52.6	72,857	0	0	0	316	157

Table 3
Annualized cost for main components of the hybrid PV/diesel system.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	840,000	224,500	15,340	0	−125,819	954,020
Diesel generator	4500	3376	27,689	537,537	−553	572,549
Surette 6CS25P	187,500	122,752	38	0	−35,241	275,049
Converter	36,000	14,083	575	0	−2621	48,037
System	1,068,000	364,710	43,642	537,537	−164,235	1,849,654

- From simulation results, the PV–diesel hybrid system has a total annual electrical energy production of 231,320 kWh yr^{-1}. The biggest contributor is PV panel which produces 74% of the total electrical energy production (170,234 kWh yr^{-1}).

5.2. The grid connected PV hybrid system

- The HOMER software completed the simulation within only 16 s.
- The least COE of this system is \$0.217 kWh^{-1} and results from the combination of 10 kW PV panel, 15 kW power converter, 1000 kW grid. But, its renewable fraction is just 0.08.
- When considering that renewable fraction is greater than 25%, the hybrid power system including a 40 kW PV panel, 25 kW power converter, and 1000 kW grid has the least COE of \$0.256 kWh^{-1} besides that, its renewable fraction becomes 31%.
- When regarding environmental effects of these two hybrid systems with least COE, with an increase in the value of renewable fraction from 0.08 to 0.31, the emission rates of CO_2, NO_x, CO and SO_x can be reduced about 20%.
- The distribution of annualized cost for each component of the PV–grid hybrid power system with the renewable fraction of 0.31 is presented in Table 4.
  The capital cost, total NPC and COE for the optimal hybrid system are \$300,000, \$838,768 and \$0.256 kWh^{-1}, respectively. For this hybrid system, the grid has the most expensive cost which is equal to \$471,644. It is followed by PV and converter costs.
- According to the simulation results, the grid connected PV hybrid system has a total electrical energy production of 184,008 kWh yr^{-1}. 69% of it is supplied by grid purchases and the rest is served by PV panels. Furthermore, operational and maintenance cost of the hybrid system makes up to almost 60% of the total cost.

Table 4
Annualized cost for main components of the grid connected PV hybrid system.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	280,00	147,901	7412	0	−98,282	337,031
Grid	0	0	471,644	0	0	471,644
Converter	20,000	13,041	463	0	−3413	30,092
System	300,000	160,943	479,519	0	−101,694	838,768

5.3. The standalone PV–fuel cell hybrid system

- The HOMER software completed the simulation within 2 min and 6 s.
- According to the optimization results, the optimum configuration for this hybrid system contains a 190 kW PV panel, 5 kW fuel cell, 40 kW power converter, 800 kW battery bank, 5 kW electrolyzer and 40 kg hydrogen tank and has the least COE, \$1.051 kWh^{-1}.
- Renewable fraction of the optimum hybrid system is 1 because there is neither electricity production from diesel generator nor electricity purchasing from the grid. Regarding environmental effects of the hybrid system with the least COE, emission rates of CO_2, NO_x, CO and SO_x are nearly zero.
- According to the simulation outputs about how often fuel cell generator is operated in the system, the fuel cell power generator operates for only 24 h during the 1 yr period. It means that there would be no more contribution from the fuel cell power generator to the total electricity production of the hybrid system.
- The distribution of annualized cost for each component of the stand-alone PV–fuel cell hybrid system is presented in Table 5.
  The capital cost, total NPC and COE for the optimal hybrid system are \$2,439,000, \$3,446,346 and \$1.051 kWh^{-1}, respectively. The most expensive cost, \$1,709,984 draws from the battery which makes up about half of the total cost. The battery cost is followed by the PV cost with \$1,600,900.

Table 5
Annualized cost for main components of the standalone PV/fuel cell hybrid system.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	1,330,000	702,531	35,207	0	−466,839	1,600,900
Fuel cell	15,000	0	44	0	−6552	8492
Surette 6CS25P	1,000,000	1,150,433	0	0	−440,448	1,709,984
Converter	32,000	20,866	741	0	−5460	48,147
Electrolyzer	10,000	5217	1853	0	−1365	15,705
Hydrogen tank	52,000	0	11,118	0	0	63,118
System	2,439,000	1,879,046	48,964	0	−920,664	3,446,346

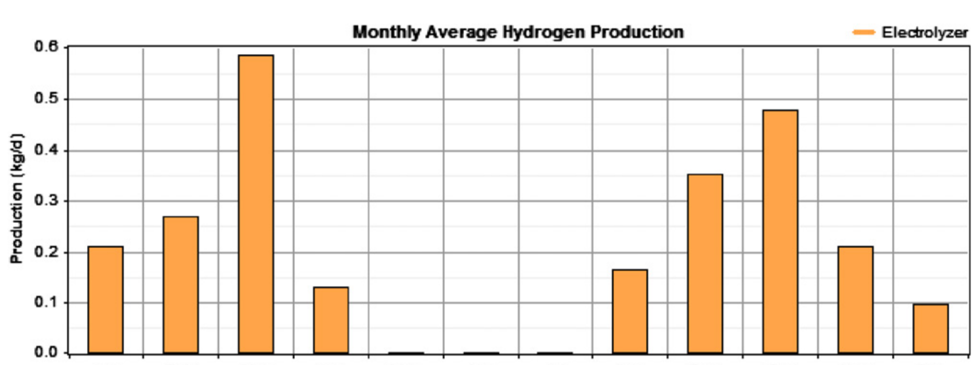

Fig. 7. The amount of yearly hydrogen production.

As seen from Table 3, PV cost is followed by hydrogen tank, converter, electrolyzer and fuel cell with $63,118, $48,147, $15,705 and $8492, respectively.

- According to the simulation results, the PV–fuel cell hybrid system generates total electrical energy production, 269,538 kWh yr^{-1}. Nearly all of this value is generated by the PV panel.
- The monthly hydrogen production of the 5 kW electrolyzer can be seen from Fig. 7. According to Fig. 7, hydrogen is mostly produced in the months of March, October and September with 0.58 kg d^{-1}, 0.48 kg d^{-1} and 0.35 kg d^{-1}, respectively. Meanwhile, the amount of yearly hydrogen production is 75.6 kg.

5.4. The grid-connected PV–fuel cell hybrid system

- The HOMER software completed the simulation within 1.5 min.
- According to the optimization results, the best configuration of this hybrid system contains a 50 kW PV panel, 10 kW fuel cell, 30 kW power converter, 10 kW electrolyzer and 20 kg hydrogen tank and has the least COE, $0.294 kWh^{-1}.
- Regarding the hybrid systems whose renewable fraction is at least 0.25, the renewable fraction value for the optimum hybrid system becomes 0.38.
- When regarding environmental effects of this optimum hybrid system, emission rates of some pollutants such as CO_2, SO_x, NO_x, CO, unburned hydrocarbons and particulate matter are 72,857 kg yr^{-1}, 316 kg yr^{-1}, 157 kg yr^{-1}, 0.338 kg yr^{-1}, 0.0375 kg yr^{-1} and 0.0255 kg yr^{-1}, respectively.
- According to the simulation outputs about how often fuel cell generator is operated in the system, the fuel cell power generator operates for only 16 h during the 1 yr period. It means that there would be no more contribution from the fuel cell power generator to the total electricity production of the hybrid system.
- The distribution of annualized cost for each component of the stand-alone PV–fuel cell hybrid system is presented in Table 6.
- The capital cost, total NPC and COE for the optimal hybrid system are $450,000, $964,381 and $0.294 kWh^{-1}, respectively. The most expensive cost, $427,239 draws from the grid which makes up about half of the total cost. The grid purchasing cost is followed by the PV cost with $421,289.
- The PV cost is followed by the hydrogen tank, converter, electrolyzer and fuel cell costs.
- According to the simulation results, the grid connected PV–fuel cell hybrid system generates total electrical energy with an amount of 186,370 kWh yr^{-1}, 70,931 kWh yr^{-1} is generated by PV panel and the rest is served by the grid.
- The monthly hydrogen production of the 5 kW electrolyzer can be seen from Fig. 8. According to Fig. 8, hydrogen is mostly produced in the months of March, February, September and December with 0.265 kg d^{-1}, 0.195 kg d^{-1}, 0.18 kg d^{-1} and 0.175 kg d^{-1} respectively. Additionally, the amount of yearly hydrogen production is 52.6 kg.

Table 6
Annualized cost for main components of the grid connected PV/fuel cell hybrid system.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	350,000	184,877	9265	0	−122,852	421,289
Fuel cell	30,000	0	59	0	−13,286	16,773
Grid	0	0	427,239	0	0	427,239
Converter	24,000	15,650	556	0	−4095	36,110
Electrolyzer	20,000	10,433	3706	0	−2730	31,409
Hydrogen tank	26,000	0	5559	0	0	31,559
System	450,000	210,959	446,385	0	−142,964	964,381

6. Conclusions

Some major outputs which were achieved in the study are given as follows:

- Fuel consumption and emission rates in the stand-alone PV–diesel hybrid system is 74% lower than the diesel system excluding a power supplier fueled by solar energy. Similarly, of the stand-alone PV–diesel hybrid system is fairly low compared to the diesel system.
- Regarding the environmental effects of the optimum stand-alone PV–fuel cell hybrid system, the emission rates are very low and nearly zero because there is neither electricity production from diesel generator nor electricity purchasing from the grid in this hybrid system.
- Fuel cost in the diesel system occupies nearly 100% of the total cost. Only $4500 is the capital cost while total cost and fuel cost are $2,315,640 and 2,311,140 , respectively.
- The stand-alone hybrid systems have the highest COE because they have expensive energy storage equipments (Battery bank and power converters) in contrast to the grid connected systems. The battery and converter costs of the stand-alone PV/diesel hybrid system cover nearly 20% of the NPC. Meanwhile, since there is no battery used in the grid connected PV/fuel cell hybrid system, there is no cost inquired due to batteries. It concludes

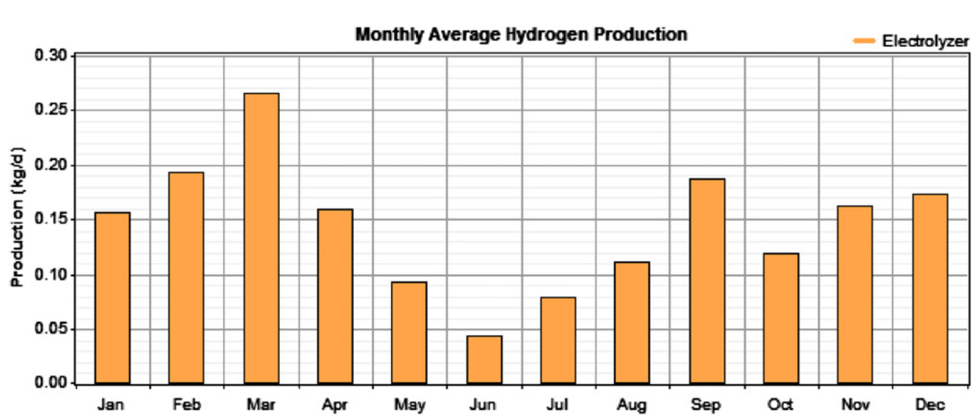

Fig. 8. The monthly hydrogen production of the grid connected PV–fuel cell hybrid system.

that there is only converter cost in the system, covering only about 3% of the NPC of the system.

- In general the grid connected systems provide cost-effective solutions.
- The grid-connected PV hybrid system has the lowest COE ($0.256 kWh^{-1}) and NPC ($82,000).
- On the other hand, the grid-connected PV/fuel cell hybrid system with COE, $0.294 kWh^{-1} that has a slightly higher cost than the grid-connected PV hybrid system. This system may be chosen because its renewable fraction is higher and its gas emission rates are fairly low. Thus, it is cleaner and environmentally friendlier when compared to the grid-connected PV hybrid system.

Acknowledgments

I am fairly thankful to the TEIAS and Turkish State Meteorological Service for providing the load data and solar data of the Kavakli campus of Kirklareli University, respectively. Also, I would like to thank Kirklareli University for supporting this study.

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